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SHORT COURSE ON
RIVER ICE ENGINEERING

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LECTURE NOTES ON ICE JAMS

by

S. Beltaos

Environmental Hydraulics Section,
Hydraulics Division,
National Water Research Institute,
Burlington, Ontario.

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FOREWORD

The Short Course on River Ice Engineering was sponsored by the N.R.C. Subcommittee on Hydraulics of Ice Covered Rivers, the N.B. Subcommittee on River Ice and the University of New Brunswick. The topics of the Short Course included formation and decay of ice covers, hydraulics of ice covered rivers, ice properties, ice jams, ice forces on structures and river ice control. The Course instructors were B. Michel, C.R. Neill, H.T. Shen and S. Beltaos. This report summarizes lecture notes by S. Beltaos (Ice Jams) and has been prepared in accordance with Divisional requirements and procedures, including reviews by Dr. T.M. Dick, Chief, Hydraulics Division and Dr. Y.L. Lau, Head, Environmental Hydraulics Section.

AVANT-PROPOS

Le cours condensé sur le génie de la glace de rivière était parrainé par le Sous-comité sur l'hydrodynamique des rivières recouvertes de glace du CNRC, le Sous-comité du N.-B. sur la glace de rivière et l'université du Nouveau-Brunswick. Parmi les sujets traités dans ce cours mentionnons: la formation et la dégradation des couvertures glacielles, l'hydrodynamique des rivières recouvertes de glace, les propriétés de la glace, les embâcles, les forces exercées par la glace sur les structures et la lutte contre la glace de rivière. Les chargés de cours étaient: B. Michel, C.R. Neill, H.T. Shen et S. Beltaos. Le présent rapport résume les notes de cours de S. Beltaos (embâcles) et a été préparé conformément aux exigences et procédures de la division avec revues par le Dr. T.M. Dick, chef de la Division de l'hydraulique, et le Dr. Y.L. Lau, chef de la Section de l'hydraulique environnementale.

ABSTRACT

River ice jams can cause many hydrotechnical problems of which flooding is the most conspicuous. Ice jams are extremely complex phenomena and the attendant mechanisms of initiation, evolution and release are poorly understood. Under the simplifying assumption of equilibrium conditions, the granular-mass theory of ice jams, as developed and calibrated in the past two decades, provides reasonable estimates of the water stage. However, equilibrium conditions do not always occur in nature and thus only potential freeze up and breakup water levels can be estimated from the ice jam theory. Surge-line phenomena, caused by ice jam releases can be modelled, to a degree, by ignoring the presence of the moving ice. Mitigation measures include ice and river modification and depend largely on experience and familiarity with local conditions. Monitoring of ice conditions is a major step toward development of forecasting techniques and response procedures at problem sites.

RÉSUMÉ

Les embâcles causent un grand nombre de problèmes hydrotechniques dont l'inondation est le plus évident. Les embâcles sont des phénomènes extrêmement complexes et les mécanismes associés au début de leur formation, à leur évolution et à leur dislocation sont encore mal compris. Suivant l'hypothèse simplificatrice des conditions d'équilibre, la théorie de la masse granulaire des embâcles, telle que formulée et étalonnée au cours des deux dernières décennies, fournit des estimations raisonnables des niveaux d'eau. Toutefois on ne retrouve pas toujours des conditions d'équilibre dans la nature et la théorie des embâcles ne permet ainsi d'estimer que les niveaux d'eau potentiels à l'englacement et à la débâcle. Les phénomènes de ligne de surpression causés par la dislocaton des embâcles peuvent être modélisés, dans une certaine mesure, en ignorant la présence de la glace en mouvement. Les mesures de lutte englobent des modifications de la glace et des cours d'eau et dépendent en grande partie de l'expérience et du degré de familiarité avec les conditions locales. La surveillance des conditions glacielles constitue une étape majeure en vue de l'élaboration de méthodes de prévision et de procédures de réaction aux emplacements problématiques.

MANAGEMENT PERSPECTIVE

These lecture notes contain up-to-date knowledge on ice jams, including descriptions of jam initiation, current theories and methods of calculating jam stage and modelling methods.

There are very few texts on ice hydraulics and these notes should be a valuable reference for all engineers and scientists interested in ice jam problems.

Y.L. Lau
A/Chief
Hydraulics Division

PERSPECTIVE DE GESTION

Ces notes de cours renferment des connaissances à jour sur les embâcles, dont des descriptions du début de la formation des embâcles, les théories et méthodes actuelles de calcul des niveaux pendant l'embâcle ainsi que les méthodes de modélisation.

Il n'existe que très peu de textes sur l'hydraulique et la glace et ces notes devraient constituer une référence précieuse pour les scientifiques et les ingénieurs intéressés par les problèmes d'embâcles.

Y.L. Lau
Chef intérimaire
Division de l'hydraulique

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INTRODUCTION

A major consequence of ice formation in rivers is the jamming that occurs during the breakup of the ice cover and (less importantly) during the freeze up period.

Ice jams can cause very high water levels even with moderate discharge, because of:

(a) the large hydraulic resistance of their underside (Manning Coeff. up to ~0.10); and

(b) their large aggregate thickness (up to several metres).

The water level must rise to accommodate: the flow depth under the jam that is needed to pass the prevailing discharge; and the submerged portion of the jam's thickness (~9/10 of total thickness).

The result can be flooding, damage to structures, channel erosion, ... (see also Table 1).

Ice jams are extremely complex phenomena and appropriately described by Uzuner and Kennedy (1976) as "at best, chaotic disorderly untidy affairs". It is thus not surprising that most aspects of ice jams remain either insufficiently or not at all understood, i.e., mechanisms of initiation, formation and release; design criteria for control measures.

DEFINITION

(IAHR): "An accumulation of ice at a given location which, in a river, restricts the flow of water"

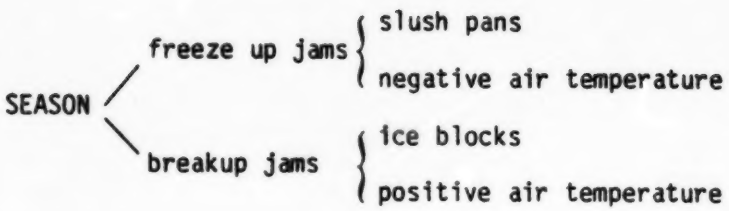
TABLE 1. Selected Case Histories

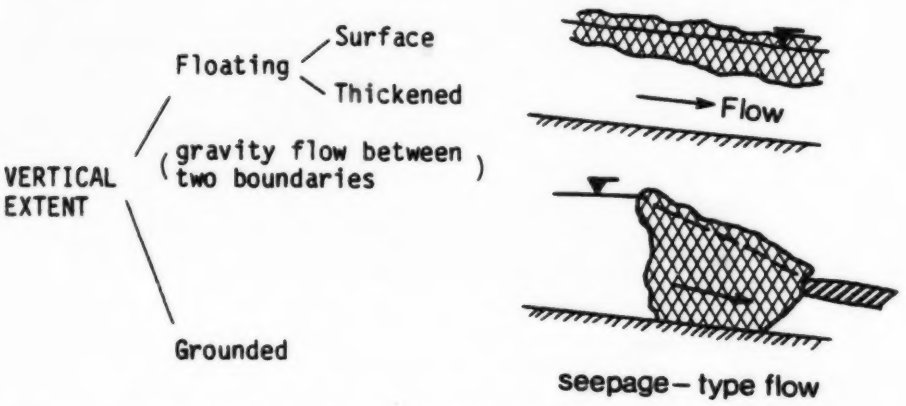
Ice Jam Location (Alberta)	Year of Occurrence	Source	Return Period of Equal-Maximum Stage Summer Flood (yrs)	Remarks
South Saskatchewan River above Sandy Point	1974	Gerard (1975)	>3	Floating surface jam, initiated by "arching" of ice floes
Peace River near town of Peace River	1974	Beltaos (unpublished data)	>100	Floating thickened jam, possibly grounded at toe. Second highest breakup stage during 1974-79
Athabasca River near Fort McMurray	1974	Gerard (1975)	>100	Grounded toe
	1977	Doyle (1977)	>100	Grounded toe
	1978	Doyle (1978)	>100	Grounded toe
	1979*	Doyle (1979)	>100	Grounded toe
Wapiti River near Grande Prairie	1976	Beltaos (unpublished data)	70	Floating, thickened jam; likely floating toe
Smoky River near the mouth	1976	Beltaos (unpublished data)	≈400	Likely grounded toe; the 1976 stage was exceeded by at least 2 m in 1979 (1000 yr?)

* During this breakup, a relative stage excess of 4.5 m was recorded at a location some 12 km upstream of Fort McMurray

NOTE: Some of the quoted return periods are based on extrapolations of frequency curves derived from relatively short periods of record which may or may not be an accurate reflection of reality. However, these return periods do show that very rare open-water flood stages can be attained when ice jams are present.

TYPES OF ICE JAMS





Often, both floating and grounded regions exist within the same jam. Grounding usually occurs at the toe (downstream end of jam) and at shallow areas, e.g. banks and bars.

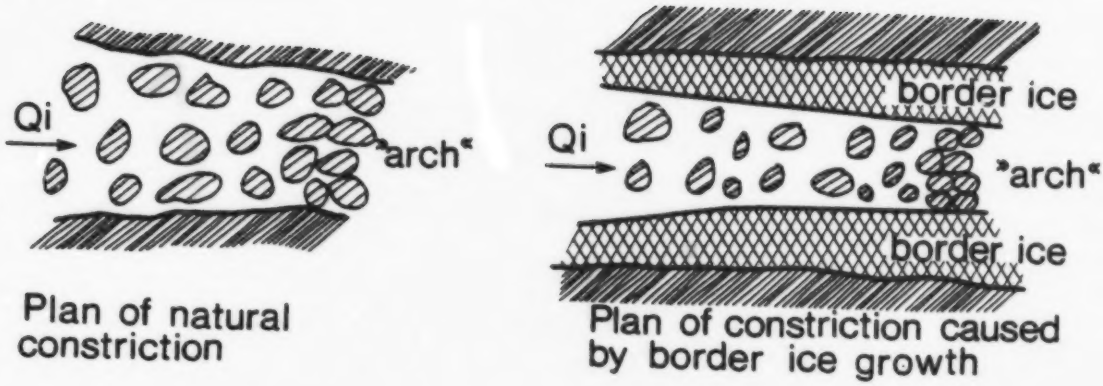
INITIATION OF ICE JAMS

Ice jams can be initiated by any obstruction to the movement of ice fragments in a river, e.g., one or more of: stationary ice cover, constrictions, bends, shallows, slope reductions, bridge piers.

Mechanisms studied so far include:

1. Surface Congestion

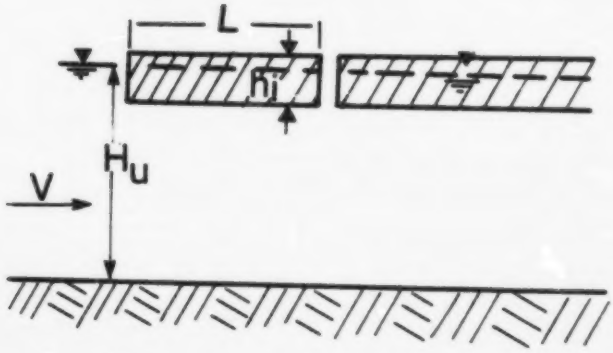
   ice discharge > local ice transport capacity → initiation of a surface jam, as illustrated below.



Surface Congestion is very common during freeze up; less common during breakup.

Details of various studies are given in: Frankenstein and Assur (1972); Calkins and Ashton (1975); Tatinclaux and Lee (1978).

2. Floating Transverse Obstacle (e.g., ice cover)



The stability of a floating ice block that has come to rest against a transverse obstacle has been studied extensively.

Depending on the block characteristics and pressure distribution on its wetted boundary, the block may or may not submerge under the obstacle. Ashton's simple theory gives good results under most practical conditions (see Ashton 1978 for details and a review of other studies):

$$V_C / \sqrt{(1 - s_i)gh_i} = 2\,(1 - \frac{h_i}{H_u}) / \sqrt{5 - 3\,(1 - \frac{h_i}{H_u})^2} \qquad (1)$$

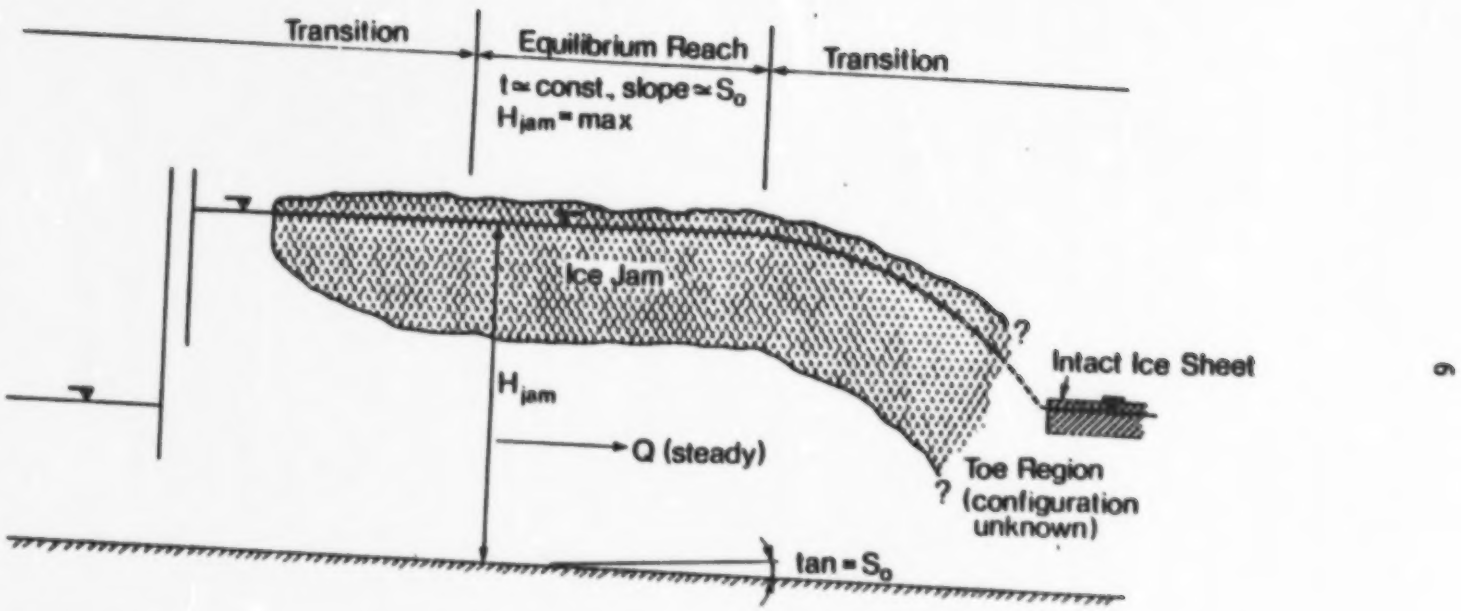
in which V_C = "critical" velocity such that a block of thickness h_i submerges when $V > V_C$; g = acceleration of gravity; s_i = specific gravity of ice. If $V < V_C$, a surface jam will be initiated. If $V > V_C$, a thickened jam may form depending on the transportability of the blocks under the obstacle (see also Tatinclaux and Gogus 1981). If $V > V_C$ and $L \geq H_u$, a grounded jam may be initiated but little else is known about this phenomenon (Mathieu and Michel 1967). If the blocks are not made of solid ice, such as slush pans, the porosity of the blocks may be an important parameter (Michel 1971).

The above results are principally founded on laboratory tests and implicitly assume that ice is unbreakable. In nature, however, violent ice runs are often observed to arrive at intact ice cover edges where they eventually come to a halt after intense breaking and piling up. It is unlikely that the submergence criterion can alone describe such phenomena and thus research is needed with simulated breakable covers.

EQUILIBRIUM OF ICE JAMS - GRANULAR MASS THEORY

Once a stable toe has formed, the jam lengthens upstream but it is not clear at present how thickness and length vary with time during this phase.

Under certain conditions a jam can attain a steady state and, if long enough, it may have an equilibrium reach (see sketch on next page). The equilibrium reach is characterized by constant jam thickness and flow depth so that the slope of the water surface is equal to that of the channel bed. Moreover, it can be shown that the



PROFILE OF A FLOATING JAM WITH AN EQUILIBRIUM REACH

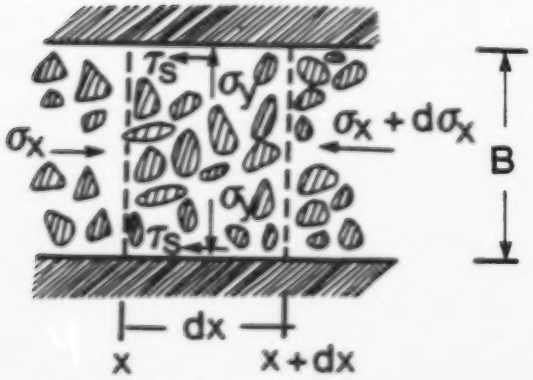
water depth attains a maximum value in the equilibrium reach. Under these conditions some theoretical reasoning has been possible, as outlined next. The jam is considered a floating granular mass and the internal stresses are calculated in terms of the applied forces.

The theory evolved since the late fifties through the efforts of numerous investigators, notably Kennedy (1958); Berdennikov (1964); Pariset, Hausser and Gagnon (1966); Michel (1971); Uzuner and Kennedy (1976).

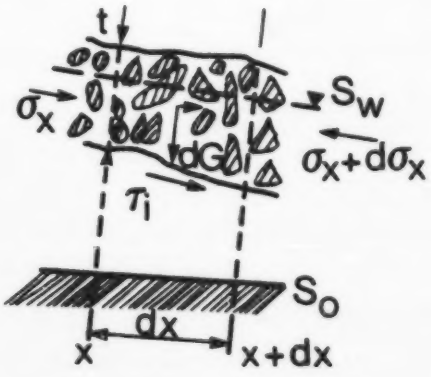
Assumptions

1. Ice jam is a floating granular mass
2. Seepage through the voids of the jam is negligible.
3. Flow and jam configuration are steady.
4. Channel is prismatic and rectangular with large width-to-depth ratio → flow depth and jam thickness do not vary in the transverse direction.
5. Cosines of small angles (whose tangent is of the order of the water surface slope) are ≈1.0.

Analysis: stresses on ice jam



Plan view of jammed channel



Longitudinal section

σ_x, σ_y = effective, thickness-averaged stresses in the x (longitudinal) and y (transverse) directions, respectively

τ_s = shear stresses that develop at the sides of the jam

τ_i = flow shear stress on jam underside

S_W = slope of water surface

S_o = slope of channel bed

dG = weight of ice and water within the element of width B, thickness t, and length dx.

Force balance +

$$(\sigma_x tB)_x - (\sigma_x tB)_{x+dx} - 2\tau_s t dx + \tau_i B dx + (dG)S_W = 0 \qquad (2)$$

Note: $(\sigma_x tB)_x - (\sigma_x tB)_{x+dx} = -\frac{d}{dx}(\sigma_x tB)dx;$ (2a)

and: $\tau_s = C_i + \lambda\sigma_y$ (2b)

with C_i = cohesion of the jam; and $\lambda = \tan\phi$ = coefficient of internal friction of the jam; ϕ = angle of internal friction. Moreover:

$$\sigma_y = k_o\sigma_x \qquad (2c)$$

with k_o = coefficient of lateral thrust.

Assuming that the porosity of the jam is the same both above the water surface and below it, it can be shown that the emerging portion of the jam is = $(1 - s_i)t$ while the submerged portion is = $s_i t$. With this result, dG can be calculated as follows (note p = porosity of the jam, ρ = water density)

$$\frac{dG}{B} = \rho g\, s_i\, t\, dxp \text{ (weight of pore water per unit width)} +$$

$$s_i \rho g\, tdx(1-p) \text{ (weight of ice per unit width)} =$$

$$s_i \rho g\, tdx$$

$$\text{or} \quad dG = s_i \rho g\, Btdx \tag{2d}$$

$$\text{and} \quad (dG)S_w = w_i\, Bdx \tag{2e}$$

with $w_i = s_i \rho g t S_w$ = streamwise component of jam's own weight per unit surface area.

Substituting these results (2a - 2e) in Eq. 2 and re-arranging, we obtain:

$$\frac{d}{dx}(t\sigma_x) + 2(C_i + \lambda k_o \sigma_x)\frac{t}{B} = \tau_i + w_i \tag{3}$$

Pariset et al. (1966) assumed equilibrium conditions throughout the jam (not entirely correct), i.e., t = const, depth = const. and (consequently) $S_w = S_o$. Eq. 3 then becomes an ordinary, first-order linear differential equation for σ_x and can be integrated readily. The result is:

$$\sigma_x = \sigma_{x\infty} + (\sigma_{xo} - \sigma_{x\infty})\, e^{-\frac{2k_o \lambda x}{B}} \tag{4}$$

in which σ_{xo} = value of σ_x at the leading edge (or head) of the jam, i.e., at x = 0; and $\sigma_{x\infty}$ is the value of σ_x when $x \to \infty$, given by

$$\sigma_{x\infty} = \frac{1}{2k_o \lambda}\left[\frac{(\tau_i + w_i)B}{t} - 2C_i\right] \tag{5}$$

Note that σ_x becomes effectively equal to $\sigma_{x\infty}$ when $2k_0\lambda x/B = 4$. From force measurements on ice booms, Berdennikov deduced a value of 1.0 for the product $2k_0\lambda$. Thus, Eq. 4 would suggest that $\sigma_{x\infty}$ is approached within a few channel widths from the head of the jam.

Examination of Eq. 4, indicates that σ_x may increase or decrease with x, depending on the sign of $\sigma_{xo} - \sigma_{x\infty}$, i.e.:

(i) $\sigma_{xo} > \sigma_{x\infty}$: The value of σ_x decreases in the downstream direction and is largest at $x = 0$. The jam is thicker than required by its strength, provided σ_{xo} < compressive strength of the jam. This is the case of "narrow" channel jams whose thickness is governed by the well-known "no spill" condition at the head:

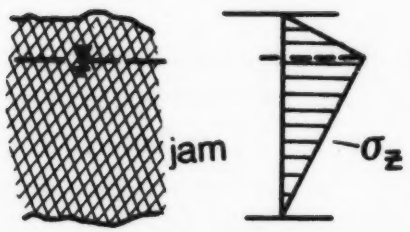
$$t = \frac{V^2}{2(1-s_i)g} \qquad (6)$$

in which V = average flow velocity under the jam.

(ii) $\sigma_{xo} < \sigma_{x\infty}$: The value of σ_x increases in the downstream direction. The thickness of the jam is governed by strength considerations, i.e.

$$\sigma_{x\infty} = \text{compressive strength of jam} \qquad (7)$$

This is the well-known "wide" channel jam and, as shown by Beltaos (1983c), should be by far the most common occurrence in natural streams. The compressive



strength of the jam is assumed to be proportional to the confining pressure, σ_z, which develops via buoyancy forces. The distribution of σ_z is as shown on the sketch. The average value of σ_z is

$$\overline{\sigma_z} = \frac{1}{2}(1-p)(1-s_i)s_i\rho gt \quad (8)$$

The compressive strength of the jam is then taken as $k_x\overline{\sigma_z}$ with k_x = coefficient of passive resistance. For a cohesionless jam (usual case during breakup), k_x is given by

$$k_x = \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \quad (9)$$

Equating $\sigma_{x\infty}$ (Eq. 5) to $k_x\overline{\sigma_z}$ gives, after some manipulation:

$$\mu s_i(1-s_i)\rho gt^2 + 2C_i t = B(\tau_i + w_i) \quad (10)$$

in which

$$\mu = k_0\lambda k_x(1-p) \quad (11)$$

Returning momentarily to Eq. 3, we may note that integration becomes very difficult if the assumption t = const. is not made (see also Uzuner and Kennedy 1976). However, Eq. 10 can again be obtained from Eq. 3 by restricting attention to the equilibrium reach where $\frac{d}{dx} = 0$, $\sigma_x = \sigma_{x\infty}$, etc. This approach is more rigorous than Pariset

et al's, but does not bring out the "narrow"-"wide" channel jam distinction as simply as done by Pariset et al.

From field measurements, Pariset et al. evaluated the coefficients of Eq. 10 and found that $\mu = 1.28$ and $C_i t = 1090$-1330 N/m. It appears that cohesion has little effect in Eq. 10 and could, as a first approximation, be neglected. This is a fair assumption for breakup jams but not necessarily realistic for freeze up ones. During freeze up, negative air temperatures may cause significant cohesion between ice blocks due to water supercooling, or even development of shear strength by formation of a thin layer of solid ice. Considering Eq. 11 and putting $\mu = 1.28$; $p = 0.4$ (usually quoted value though porosity of natural jams has not been measured); and $k_o\lambda = 0.5$ as suggested by Berdennikov (1964), gives $k_x = 4.27$. For cohensionless jams, Eq. 9 can then be utilized to estimate ϕ. This results in $\phi = 38.3°$; then, $\lambda = \tan\phi = 0.79$ which would suggest that k_o, the coefficient of lateral thrust, is equal to $0.5/0.79 = 0.63$. These values are, of course, tentative because they are based on assuming $k_o\lambda = 0.5$ which is a value obtained by only one investigator.

Additional studies (Calkins 1983 and Beltaos 1983c) have corroborated Pariset et al's value of μ while showing that cohesion did not seem to be important. It is noted that the thickness of ice jams is usually not measurable, except under special conditions (see, for example, Calkins 1983). However, the water level profile along an ice jam can be determined. A convenient method to do this is to photograph the stage of the jam against identifiable features on the river banks at a sufficient number of locations along the jam. The jammed reach can be visited later during open water conditions and the photographs examined to identify and survey the jam stages. An example is shown in Figure 1. More examples may be found in Doyle (1977); Doyle and Andres (1978) and (1979); Beltaos (1981) and (1983a).

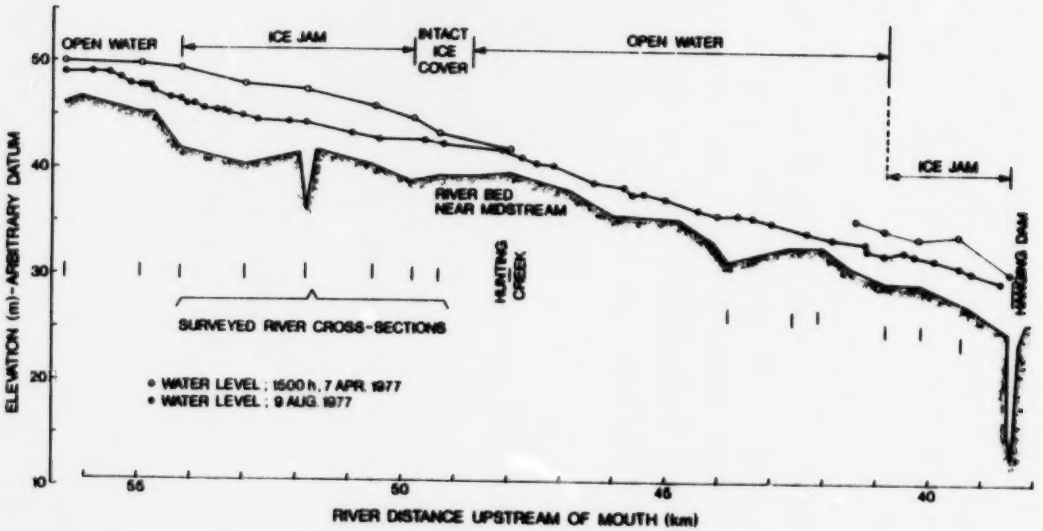


Fig. 1. Profiles of Smoky R. (Alberta) under Open-Water and Ice Breakup Conditions (38 km to 56 km above the mouth); Note two ice jams caused by local reduction in slope and hanging frazil ice dam respectively (from Beltaos 1980).

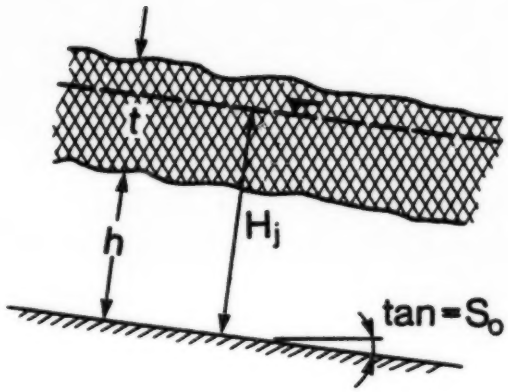
CALCULATION OF JAM STAGE

Eq. 10 shows that the thickness, t, of an equilibrium "wide" jam can be calculated in terms of flow and channel characteristics as well as properties of the jammed ice accumulation.

However, the usual problem in practice is how to calculate the stage caused by an ice jam, given the channel geometry and flow discharge. To do this, we assume that:

- The jam is of the floating, equilibrium, "wide" channel type. Flow through the voids of the jam is neglected.
- The river can be replaced by a very wide rectangular channel of equivalent average dimensions. The flow is assumed to be "uniform" in a "reach-average" sense. Note that strict uniformity cannot exist in natural streams, especially when covered by a thick and rough ice accumulation. However, "reach-average" uniformity does occur and means that fluctuations about average values are present but the average values do not vary in the downstream direction.
- Special constraints, e.g., low flood plains, bypass channels and the like, are ignored.

Problem: Given S_o, Q and channel geometry, predict H_j = overall water depth caused by an ice jam. Channel geometry is given in terms of representative cross-sections from which "reach-average" geometry can be deduced.



Profile in equilibrium reach of a jam

Assuming that the porosity of the jam is the same both above and below the water surface, it can be shown that the submerged portion of the jam's thickness is $s_i t$ (=0.92t). Hence:

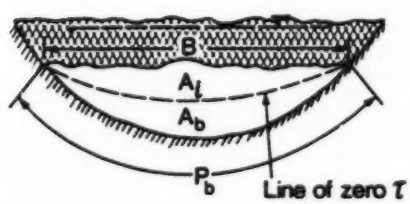
$$H_j = h + s_i t \qquad (12)$$

To calculate t, we start with Eq. 10 which, after neglect of cohesion, reads:

$$\mu s_i(1-s_i)\rho g t^2 = \tau_i + s_i \rho g S_o t \qquad (13)$$

Note that w_i has been replaced by $s_i \rho g S_o t$, as was shown on p. 9 (following Eq. 2e); moreover, S_w has been set equal to S_o, given that we are dealing with the equilibrium reach.

Our earlier relationships, derived for two-dimensional flow under the jam, may now be adapted to the river cross-section by subdividing the flow area in terms of the line of zero shear stress (τ). Then we can work in terms of the respective hydraulic radii, R_i and R_b. Note that $R_i = A_i/B$ and $R_b = A_b/P_b = A_b/B$. Moreover, h = average flow depth = $(A_i + A_b)/B$ or $h = R_i + R_b$.



Now, τ_i can be expressed as:

$$\tau_i = \rho g R_i S_o \tag{14}$$

Moreover, $R_i/R_b = f_i/f_b$ (Beltaos 1983c) with f_i, f_b = friction factors of the ice jam underside and of the channel bed respectively. The composite friction factor, f_o, is:

$$f_o = 0.5\ (f_i + f_b) \tag{15}$$

After some manipulation, Eq. 14 becomes

$$\tau_i = \frac{f_i}{2f_o}\ \rho g h S_o \tag{16}$$

Substituting Eq. 16 in Eq. 13 and solving for t gives (with $s_i = 0.92$)

$$\frac{t}{S_o B} = \frac{6.25}{\mu}\left\{1 + \sqrt{1 + 0.174\ \mu\left(\frac{f_i}{f_o}\right)\frac{h}{S_o B}}\right\} \tag{17}$$

For the flow under the jam, we may write:

$$f_o = 8\ g\ R_o S_o / V^2 \tag{18}$$

in which $R_o = h/2$ = composite flow hydraulic radius; and V = average flow velocity under the jam. Solving for V gives:

$$V = \sqrt{4\ g h S_o / f_o} \tag{19}$$

and thus:

$$Q = BhV = Bh^{3/2}\sqrt{4\ gS_o/f_o} \tag{20}$$

Putting $q = Q/B$ and solving for h gives:

$$h = 0.63\ f_o^{1/3}\ (q^2/gS_o)^{1/3} \tag{21}$$

Dividing Eq. 21 by S_oB gives:

$$\frac{h}{S_oB} = 0.63\ f_o^{1/3}\ \xi \tag{22}$$

in which ξ is defined as:

$$\xi \equiv (q^2/gS_o)^{1/3}/S_oB \tag{23}$$

Then, Eq. 17 becomes

$$\frac{t}{S_oB} = \frac{6.25}{\mu}\left\{1 + \sqrt{1 + 0.11\mu f_o^{1/3}\ (f_i/f_o)\xi}\right\} \tag{24}$$

Multiplying Eq. 24 by $0.92(= s_f)$ and adding to Eq. 22, gives an expression for H_j/S_oB (see also Eq. 12):

$$n \equiv H_j/S_oB = 0.63f_o^{1/3}\ \xi + \frac{5.75}{\mu}\left\{1 + \sqrt{1 + 0.11\ \mu\ f_o^{1/3}\ (\frac{f_i}{f_o})\ \xi}\right\} \tag{25}$$

which gives H_j in terms of B, S_o, Q and the coefficients μ, f_i and f_o. Some noteworthy features of Eq. 25 are:

- H_j appears only on the LHS so that it can be determined directly if B, S_o and Q are given, without resort to trial-and-error procedures.
- For given S_o and B, H_j will increase monotonically with Q, i.e., there are no maxima or minima that could complicate the picture.
- For $\xi = 0$ (i.e., $Q = 0$), n becomes equal to $11.5/\mu$, i.e., H_j will be non-zero. This implausible result is caused by the neglect of the seepage flow through the voids of the jam, as explained by Beltaos (1983c). As ξ decreases, the ratio t/H_j can be shown to increase which means that the seepage flow will become more and more significant relative to the total flow. However, very little is known about seepage through jammed ice accumulations and it is thus not possible at present to establish a lower limit for ξ, below which Eq. 25 would give erroneous results.
- The main variable on the RHS of Eq. 25 is ξ. The coefficient μ depends entirely on properties of the jammed ice accumulations and, if the theory is valid, should vary little. The ratio f_i/f_o has a relatively narrow range of variation (always between 0 and 2) while the RHS of Eq. 25 is rather insensitive to f_i/f_o. The coefficient f_o could vary from jam to jam and river to river and should thus be the main source of scatter in a plot of n versus ξ. However, f_o appears in Eq. 25 with a small exponent (1/3) and there is some evidence (Beltaos 1983c) suggesting that f_o is partly dependent on ξ. Thus, it would appear that, plotting field data in the form of n versus ξ

might result in a satisfactory relationship. This expectation is confirmed in Figure 2 where data from several rivers and sources are utilized. The attendant ranges of B, Q and S_o are respectively = 36 m to 680 m; 10 m^3/s to 3,930 m^3/s and 0.05 m/km to 4.4 m/km. The average line drawn through the equilibrium jam data points in Figure 2 could be used as a first approximation. The non-equilibrium data points are generally located below the equilibrium line, as might have been expected (maximum depth occurs under equilibrium conditions). Figure 3 is a more convenient version of Figure 2 that can be used for practical application.

Example: We are given that, at a certain site, B = 100 m; $S_o = 0.5 \times 10^{-3}$; and the breakup discharges range from 200 to 1000 m^3/s. Estimate an upper envelope for the peak breakup stages.

We have $S_oB = 0.05$ m.

- Calculate ξ from Eq. 23
- Find n from Figure 3
- Calculate $H_j = nS_oB$
- Tabulate:

Q m^3/s	ξ	n	H_j (m)
200	187	85	4.3
400	297	113	5.7
600	389	139	7.0
800	471	162	8.1
1000	547	183	9.2

These values of H_j should be considered an upper envelope because an ice jam may or may not form nearby in a given year; or it may not fully affect our site. In addition, the elevation of the flood plain is an important consideration because, once the water

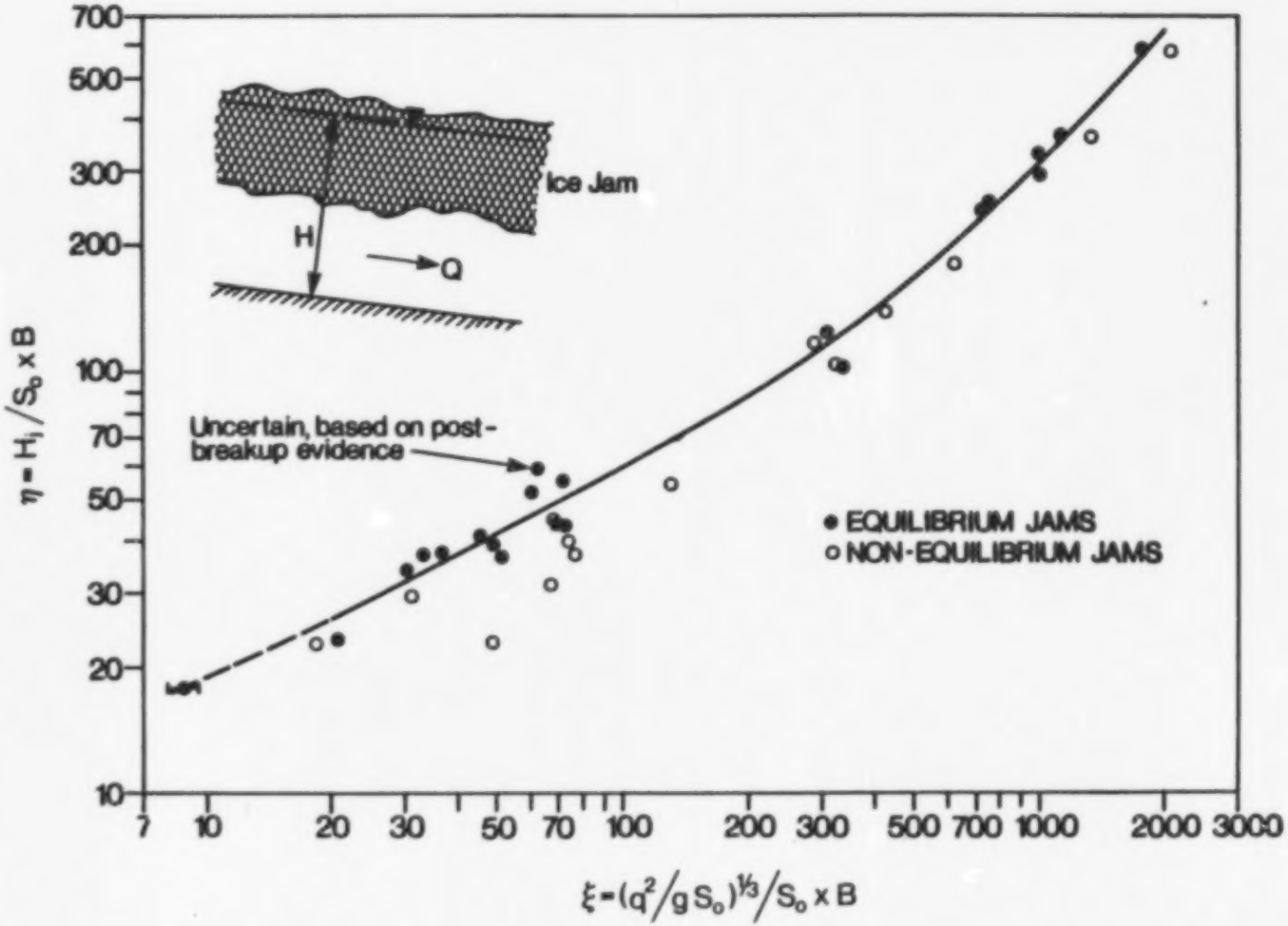


Fig. 2. Dimensionless depth versus dimensionless discharge for river ice jams. Data from: Doyle and Andres-Athabasca R; Neill and Andres-Peace R; Beltaos-Heart R, Grand R, Wapiti R, Thames R, Smoky R, Peace R.

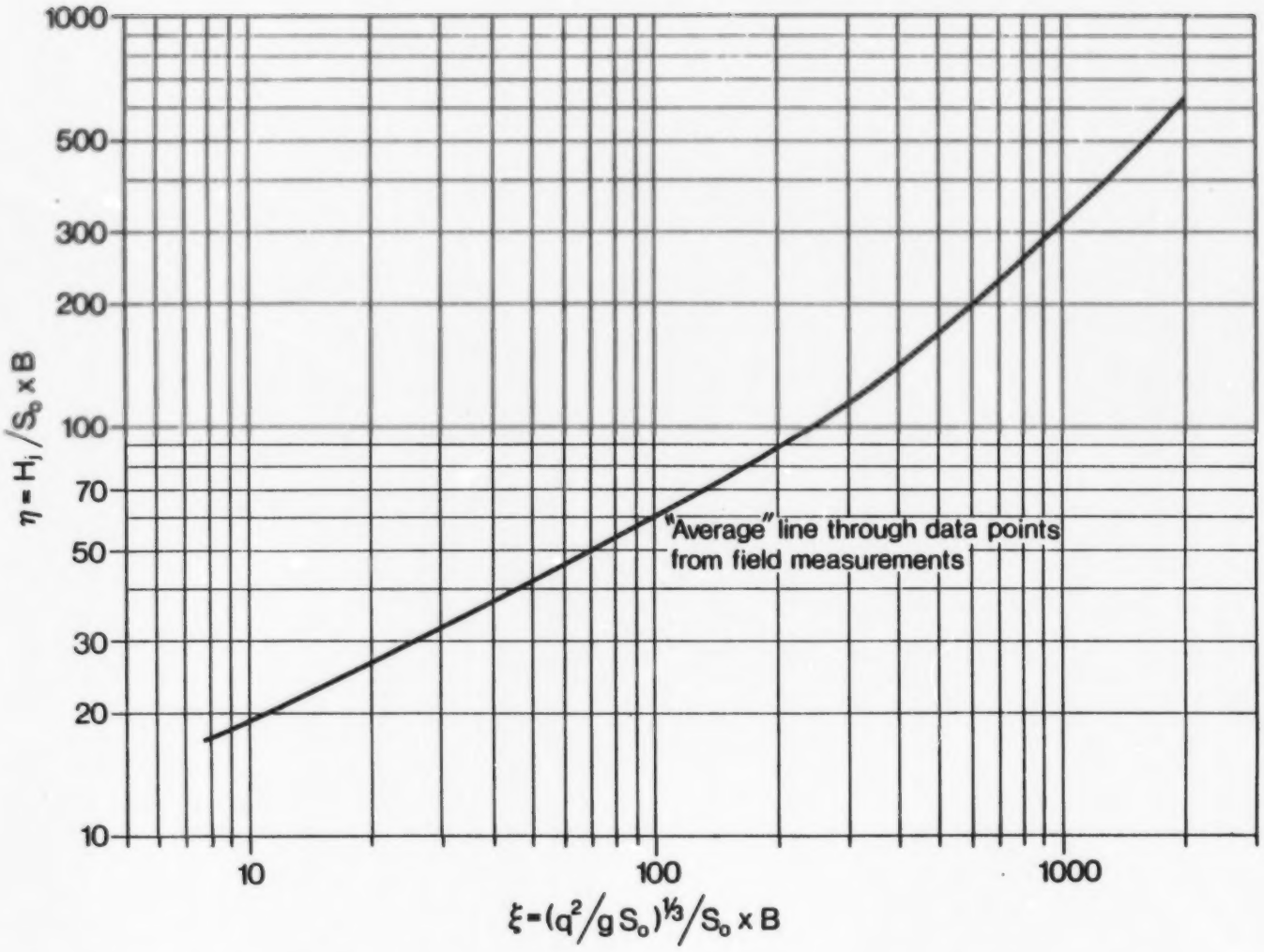


Figure 3 DIMENSIONLESS WATER DEPTH DUE TO AN EQUILIBRIUM, FLOATING, WIDE CHANNEL JAM vs. DIMENSIONLESS DISCHARGE

level exceeds it, the flow and ice will spread onto the floodplain and the jam's potential may be dissipated. A more detailed method to calculate H_j has been described by Beltaos (1983c). This method takes into account changes in width with stage and makes use of channel bed resistance characteristics if such information is available from hydrometric surveys. Resistance characteristics of the jam are evaluated from Nezhikhovskiy's (1964) data for the beginning of freeze up. The detailed method and the simple method described earlier involve considerable uncertainties and should always be supplemented by careful site inspections and historical evidence where possible. A few examples of the performance of these methods in actual situations are given in Beltaos (1983c).

THE RELEASE OF ICE JAMS

How, why and when jams release is generally unknown, but it is suspected that discharge, toe conditions and thermal effects play a role. A suddent jam release and the ensuing ice run is one of the most spectacular and violent events that occur during breakup. The stage rises very rapidly at downstream locations and water velocities far exceed even those attained during extreme open-water floods.

Examples:

Water Level Rise
- 17 m in < 1 h, Athabasca R. at Ft. McMurray, 1875 - Gerard (1979)
- 11 m in 3 h, Red Deer R. at Red Deer, 1976 - Gerard (1979)
- 1.5 m in 30 s, Moira R. at Belleville, 1981 - news item

Water Speed	≈5 to 6 m/s, Athabasca R. at Fort McMurray, Doyle (1977), Doyle and Andres (1979)
	7.6 m/s, Mackenzie R. near Point Separation, Mercer and Cooper (1977)

Modelling of ice jam releases can be done by ignoring the effect of the moving ice and assuming unsteady, one-dimensional, open-water flow (Mercer and Cooper 1977; Henderson and Gerard 1981, Beltaos and Krishnappan 1982, Joliffe and Gerard 1982, Wong et al. 1983). All of these analyses assume open-water conditions downstream of the jam which is not a frequent natural occurrence. Usually, the jam is held by intact ice cover downstream of its toe. If this cover is set in motion during the release, then the assumption of open water should still give fair results.

When an ice run is arrested due to competent ice cover or other obstacle, a new jam will begin to form and the water level upstream may rise quickly. However, it is not possible to model this phenomenon at present owing to lack of knowledge regarding conditions at the toe of the new jam.

MODELLING OF ICE JAMS

Mathematical Modelling

Mathematical modelling of ice jams and related phenomena is largely based on the existing theoretical concepts of initiation and equilibrium (see, for example Petryk et al. 1980; Carson 1982). A number of mathematical models are currently in use but most are proprietary.

Some of the difficulties with mathematical modelling of ice jams are:

- Deciding where an ice jam is to be initiated. Historical information may be useful in this regard.

- Formulating the downstream boundary condition during the jam's evolution. Little is known about the conditions at the jam toe, i.e., whether the jam is grounded or floating and what kind of discharge-depth relationship prevails at the toe.
- Formulating stability criteria at the toe which precludes predictions of whether and when an ice jam might release. This depends on local channel and ice configurations and hence on the competence of the intact ice that holds the jam in place.

Physical Modelling

In many design situations detailed data are needed that can hardly be obtained by mathematical modelling. In such instances, physical modelling presents an attractive alternative. Physical models of ice jams commonly involve the use of solid blocks or pellets that have the desired buoyancy and internal friction characteristics. Such modelling is useful but does not reproduce the effects of the breakability of intact ice covers. To do this, ice properties must be scaled down (see, for example, Kotras et al. 1977 and Michel 1978). This requirement precludes use of freshwater ice as a model material. For applications at room temperature, commonly used model materials are synthetic wax- or plaster of paris-based. Where cold room facilities are available, saline ice and doped ice can be used (Timco 1981; Hirayama 1983).

Most of the physical modelling with breakable "ice" that has been performed to date pertains to the interaction of ice with structures and ships. Applications to river ice breakup and jamming are relatively few (see, for example, Michel et al. 1973; Michel and Abdelnour, 1976). Therefore, quantitative extrapolations of model

results to prototype conditions should not be made without field verification.

MITIGATION

An extensive literature survey of control measures to alleviate breakup and jamming effects is given by Bolsenga (1968). Additional guidelines may be found in U.S. Army Corps of Engineers (1982). In general, control methods can be subdivided into ice modification and river modification, as outlined next.

Ice Modification

- Dusting: material of low albedo is spread on the ice surface to promote heat transfer; effectiveness depends on weather conditions.
- Thermal regime modification: the water temperature is altered to prevent formation of, or weaken the ice cover at critical areas.
- Ice breaking: ice breakers or other vessels are used to break the ice downstream of ice jams or at critical areas prior to breakup. Sometimes, different equipment is used to cut open leads in the cover before breakup. Ice breaking is usually effective but can be costly, (e.g., see Frietag 1980; Jolicoeur et al. 1984).
- Explosives: blasting and even bombing have been employed in the past to remove ice jams but their effectiveness is uncertain. Use of explosives in populated areas could damage nearby structures. This is clearly a last-resort measure. It is always better to prevent formation of ice jams than have to remove them.

River Modification

This approach involves more permanent measures that result in alteration of the flow pattern and river regime, i.e.:

- channelization, e.g., elimination of morphological features conducive to jamming
- erection of ice retention or diversion structures such as ice booms, dykes, dams, etc.

Because of the relative underdevelopment of the state of the art on ice jams, the design of control measures depends heavily on experience and familiarity with local conditions. Where feasible, field observations over one or more seasons are highly advisable. The performance of control measures taken at various problem sites should be monitored over several years and the findings published.

ORGANIZING RESPONSES TO ICE JAMS

Often, the response to an ice jam comes too late; the jam has already caused or is just about to cause flooding or other damage. A capability to forecast potentially dangerous situations, at least a few days in advance, is needed. In view of the present state of the art on ice jams, the best remedy seems to be systematic monitoring of ice conditions. At a given site, monitoring would, after a few seasons, help identify conditions that may lead to problems. Monitoring should aim at documenting freeze up conditions and attendant water levels; growth of ice thickness during the winter; and breakup conditions and water levels. This information could then be combined with pertinent meteorological data to formulate forecasting and warning procedures that are best suited to the site of interest. The results of the monitoring program would also help design appropriate control measures.

A feasible arrangement for monitoring is to utilize local personnel in conjunction with instruction provided by municipal or provincial authorities (e.g., Conservation Authorities, Departments of Environment or Water Resources, etc.).

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